RETROFITTING APPRAISAL OF EXISTING BUILDINGS EXPOSED TO FIRE

SHORT SYNOPSIS

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Certificate

I hereby declare that the short synopsis **"Retrofitting Appraisal of Existing Buildings Exposed to Fire"** being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in Civil Engineering under School of Engineering and Technology of Manav Rachna International Institute of Research & Studies, Faridabad during the academic year 2023-24. It is a bona fide record of original work carried out under the supervision of **Dr. Sunita Bansal**, Professor, Department of Civil Engineering, School of Engineering and Technology, and has not been submitted in full or part to any other university or institute for degree or diploma. Further, it is certified that short synopsis is plagiarism free and proof has been submitted.

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ABSTRACT

The construction of high-rise buildings has rapidly increased in the last century to cater to the growing population, office spaces, hotels, and more. Fire safety measures and building codes are designed to limit the damages caused by fire incidents, but the building components suffer a decrease in structural adequacy. Past instances of tall building failures have sparked considerable apprehensions regarding the suitability of conventional fire design standards and structural adequacy after fire for such structures. The adoption of structural fire engineering techniques can bolster the safety of tall buildings during fire incidents by fortifying weak points within the building's framework. Simultaneously, this approach can also lead to cost savings in fire protection measures by eliminating them when deemed unnecessary. Structural performance criteria may range from admissible collapse to requiring additional considerations for slow evacuation and financial value. This research will develop a criteria framework for fire safety ratings of existing buildings using rapid visual screening and analyze the behavior of high-rise buildings subjected to fire. New criteria and credits in building codes and standards, Collapse mechanisms using appropriate software and adequate retrofitting techniques will be proposed for better and safer high-rise buildings in the future.

Key Words: High Rise Building, Fire Risk Assessment, Fire Dynamics, Fire Resistant Building, Retrofitting

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Abbreviations	Description	Page No.
ASTM	American Society for Testing and Materials	1
FA	Factory Mutual	2
UL	Underwriters Laboratories	2
NFPA	National Fire Protection Association	2
SFPE	Society of Fire Protection Engineers	2
IFC	International Fire Code	4
NBC	National Building Code	4
ICC	International Code Council	4
GRIHA	Green Rating for Integrated Habitat Assessment	5
ASET	Available Safe Egress Time	6
RSET	Required Safety Egress Time	6
QRA	Quantitative Risk Assessment	7
FRAME	Fire Risk Assessment Method for Engineering	7
PAI	Priority Analysis of Safety Markers	8
FRP	Fiber Reinforced Polymer	9
DIANA	Displacement Analyser	9

HPCM	High-performance cement mortar	10
GPM	Geo-polymer mortar	10
MPCM	Magnesium phosphate cement mortar	10
SCC	Self-Compacting Concrete	11
GGBFS	Ground Granulated Blast Furnace Slag	11
CPP	Cement Perlite Plaster (CPP)	11
EPA	Expanded Perlite Aggregate	11
ISO	International Organization for Standardization	11
CFRP	Carbon Fiber Reinforced Polymers	11
CFST	Concrete-Filled Steel Tube	12
FEMFAT	Finite Element Method Fatigue	13
3D	3 Dimensional	14
ETABS	Extended 3D Analysis of Building Systems	15
SAP	Structural Analysis Program	15
GFRP	Glass Fiber Reinforced Polymers	16
BFRP	Basalt Fiber Reinforced Polymers	17

1. INTRODUCTION

Tall building development has increased dramatically in the past two decades all around the world. These structures can pose unique problems for engineers and architects due to their often inventive and complicated designs. Earlier, tall building fire incidences raised serious doubts about the application of mandatory fire design to these structures. A high-rise building's safety can be enhanced by using structural fire engineering in the event of a fire by reinforcing any weak part or member in the structure, while also lowering fire protection expenses by removing it where it is not needed.

One of the most severe risks for a building is fire; therefore, fire safety design is among the most crucial deliberations in civil construction design [1]. Standard fire tests continue to be regularly utilized and were formerly the sole basis for fire safety design. The core of the design approach for structure in fire has been standard fire testing since the primary codified ASTM E119 fire test standard in the early twenty-first century [2]. Also, it has remained essentially unaltered for more than a century.

Challenging standard views about an appropriate and conventional framework for prescribing fire safety design. In spite of these issues, high-rise structures are designed in a prescriptive manner in terms of fire situations in many parts of the world. Whereas other loads that may impact high-rise structures, like seismic and wind loads, are handled by professionals in the performance-based design aspects. Fire design is done in a formalized manner based on ideas created more than 70 to 80 years ago, where they analyze the reaction of a structure under a number of acceptable worst-case scenarios in a parametric approach.

Significant progress has been made in recent years in terms of architectural style and the implementation of modern materials used for construction. Many of them are engineered to meet all environmental criteria, yet they are extremely flammable. As a result, concerns have been raised about a potentially dangerous prescriptive design, given that mandatory codes were designed for high-rise structures with different features. So codes have limited application to current creative architecture. Performance-based engineering is a more logical approach that is truly compatible with design practice in other engineering disciplines for the structural fire design of complex structures, such as high-rise buildings [3]. Engineers and regulatory agencies have begun to recognize this as a way to show the safety of these sorts of constructions. Furthermore, the designing process allows engineers

and architects to achieve their inventive concepts without even being constrained by a set of pre-set criteria that can be circumvented only by reaching the same objectives using different methods. During 18th & 19th century in the United Kingdom and the United States, urban fires persisted during the Industrial Revolution, but they started to get reduced as non-flammable construction elements like steel, concrete, and brickwork became more widely used. However, fire danger increased as a result of newer methods for storing materials and industrial processes. During this period, several dramatic building fires took place.

The insurance industries needed to minimize property insurance losses served as the driving force behind numerous improvements in fire safety engineering during the 19th century. Factory Mutual (FM), Underwriters Laboratories (UL), and the National Fire Protection Association (NFPA) were established in 1835, 1893, and 1896, respectively. All of them were developed by insurance companies in the United States and were responsible for fire protection engineering.

Attempts were made to develop universal "Standard" fire resistance tests in the early nineties by many testing organizations in the construction sector [4]. During the first half of the 20th century, the main procedure for implementing fire protection engineering, fire codes and standards were used to safeguard life and property [5]. Various other fields like architectural, civil, electrical, and mechanical engineering, impacted many of these criteria. Fire protection engineering arose as a distinct engineering discipline in the later part of the 20th century from civil, chemical, and mechanical engineering.

The Institution of Fire Engineers was founded in 1918 in the United Kingdom Subsequently; during 1950s the Society of Fire Protection Engineers (SFPE) was founded in the United States. In 1988, the SFPE Handbook of Fire Protection Engineering [6] was issued; it was an important step in the direction of the general use of fire prevention engineering with computation techniques. The SFPE Engineering Guide to Performance-Based Fire Protection was released. It detailed the design of fire prevention systems using a performance-based approach.

The development of technology during the late 20th and early 21st centuries made it possible to quantitatively evaluate fire safety. It was first applied by fire safety experts in the 1990s. Various safety factors were given more importance. It was accomplished through developing fire and structural models that are simpler for fire safety engineers to

use, the processing capacity of modern computers, and enhanced analytical techniques for generating quantitative assessments in fire protection.

Existing codes and standards lack accuracy in representing real-world fire situations, inadequately cover the after-effects of fire on building components, provide un-quantified fire safety levels, use overly conservative approaches for fire resistance assessment, lack cost-effectiveness, suffer from a shortage of research on fire propagation in Indian buildings, and require structural analysis and adequacy assessment for retrofitting and reusing buildings with fire exposure.

The research focuses on developing a criteria framework for structural ratings using rapid visual screening of buildings exposed to fire. Additionally, various fire behavior models will be generated and analyzed using specialized software, with a focus on high-rise buildings and different fire scenarios. Collapse mechanisms will be studied through parametric analyses. The research also aims to propose new criteria and credits for building rating systems, aiding the construction of safer high-rise buildings, and will also suggest retrofitting techniques and redesign measures based on the analysis.

2. LITERATURE REVIEW

2.1 Rating System & Existing Norms for Fire Safety

Fire codes and norms are crucial for establishing safety standards in fire prevention, protection, and restoration. They cover various aspects such as prevention, building design, alarm systems, and emergency protocols. Examples include the International Fire Code (IFC), codes by the National Fire Protection Association (NFPA) and National Building Code (NBC) etc. Building codes also incorporate fire safety measures, and international standards ensure equipment reliability. These regulations require fire safety plans, inspections, and updates based on research and technology.

The standards in fire safety rules must be followed to ensure building safety. A shift from prescriptive to performance-based strategies has emerged in fire safety legislation in the past decade. "Fire Risk Assessment" assesses the probability and impact of fires but faces limitations, especially in diverse situations and building uses. Developing fire safety methodologies involves analyzing critical components. Variations may occur in the number of components considered, their weighting, mathematical models, and inclusion of factors in risk analysis. Despite differences, current fire prevention systems may not fully address contemporary fire danger concerns, as supported by relevant studies.

The National Fire Protection Association (NFPA) [7] is a prominent organization in the United States focused on fire safety. They create and publish codes and standards for fire protection, life safety, and electrical safety, offering crucial guidelines for industries and organizations to safeguard people and property. Key NFPA codes encompass NFPA 1 (Fire Code), NFPA 13 (Sprinkler Systems), NFPA 72 (Fire Alarm Systems), NFPA 101 (Life Safety Code), NFPA 70 (Electrical Code), and NFPA 20 (Fire Pump Installation). These codes are regularly updated to include the latest technology and best practices. While widely used in the United States, other countries may have their own fire safety regulations. Professionals in fire safety, architects, engineers, and building owners rely on NFPA codes for compliance and improved fire safety.

The International Fire Code (IFC) [8] developed by the International Code Council (ICC), is a widely recognized and adopted set of fire safety regulations. It guides fire prevention, protection, and life safety in buildings and covers key areas like fire prevention, alarms, sprinklers, construction materials, exits, and hazardous materials. It's a foundational

document often used as a model code by local and state jurisdictions. Regular updates reflect technology advancements and best practices, making it essential for fire safety professionals, building experts, and local authorities.

The Indian Standard for Fire, Part 4, outlines fire prevention measures for buildings, covering zoning, development restrictions, occupancy categories, and construction materials. It also addresses safety during evacuations, emphasizing egress methods and fire protection procedures. Compliance with these codes and the involvement of certified fire protection engineers are essential for effective fire prevention. The National Building Code (NBC) [9] has evolved over the years, with significant updates in 2005, dividing its content into three key clauses: "Fire Prevention" for passive safety techniques, "Life Safety" for occupant protection, and "Fire Protection" for equipment and installations, collectively strengthening fire safety in building design and construction.

Building codes and regulations comprehensively address fire prevention, mitigation, and safety, providing guidance for evaluating and designing fire-resistant structural components, as briefly explained by Kodur et al. [10]. They cover structural responses to fire, allowable fuel loads, required fire ratings, material recommendations, minimum member dimensions for fire ratings, and evacuation strategies. These recommendations vary based on occupancy types, with stricter guidelines for places like hospitals and nursing homes due to the elevated risk to human safety and potential financial consequences.

The Green Rating for Integrated Habitat Assessment (GRIHA) [11] is a well-established system in India for assessing the sustainability of buildings and habitats. In the context of GRIHA, it's important to evaluate the impact of a fire incident, considering both immediate and long-term consequences. Fires can cause structural damage, release hazardous materials, and increase energy consumption. GRIHA guidelines are essential for assessing and mitigating these environmental and energy implications during post-fire reconstruction. This involves advocating for sustainable materials, energy-efficient systems, and resilient design practices to enhance a building's overall sustainability after a fire. GRIHA provides a valuable framework for guiding recovery efforts following a fire.

Discontentment with prescriptive-based norms that are not possible to utilize as a guide to evaluating structures with particular purposes and complicated architectural designs is what led to this shift [12]. Additionally, the safety standards established by prescriptive

norms are overpriced, making it highly expensive to comply with them. Since many years ago, a performance-based strategy has gained popularity. This strategy gives building designers the chance to create creative and economical designs of regulatory solutions that are similar or superior.

The essence of the two strategies is where the fundamental distinction resides, as studied by Richardson [13]. Prescriptive-based approaches emphasize standards and rules, while performance-based strategies place more emphasis on objectives than on finding answers. Fire safety objectives are given more weight under performance-based guidelines. Performance-based regulations are regarded as being more adaptable, practical, and simple to implement because of this. Hadjisophocleous et al. [14] observed optimal design with improved safety and a cheaper cost can also be attained through performance-based regulation. Modeling and simulation may be used to do a performance-based assessment. Computer analysis may be used to perform the simulation. The behavior of residents in the case of a fire is predicted through modeling and simulation studies. Since the 1960s, this study has advanced as a model used in programs to anticipate the probability of fire danger.

The Available Safe Egress Time (ASET) Model is one of the two-part ASET and RSET approaches, which are discussed by Cooper and Stroup [15]. It is defined as the interval between detection time and the dangerous object and gives a solid estimate of when it is appropriate to impart the idea of fire safety after this safe evacuation. The Required Safety Egress Time (RSET) is a duration used to determine the maneuver of building inhabitants to a secure location to guarantee that the structure is considered secure for those residents. Fire protection strategies should be less effective in RSET than ASET, as determined by space formation. RSET is solely taken into account for travel time to the exit. Cooper did not, however, offer any advice on how to determine RSET in his hypothesis.

The researcher, Sime [16] then improves several parts of the RSET by including the period of countermeasures in initial identification and evacuation. Following the instant of being aware of the fire signal, to account for various delays before moving in the direction of the escape, the coping stage could be better understood as a pre-movement stage. Fleming et al. [17] observed that, in today's time, it has been sought to establish quantitative performance measures for the assessment of a structure's ability to prevent fire from spreading to nearby buildings or other populated areas. Comparing two or more potential

alternative techniques is how quantification is done. The ASET/RSET approach uses time as an indication to show that occupants are safe from a fire threat.

Kurniawan et al. [18] observed that fire engineering studies often entail an evaluation of the spread of the fire, the dispersion of smoke, and occupant evacuation. The idea behind this strategy is that if a straightforward ASET is greater than the RSET connection reached, it can be presumed that the building's performance in the presence of a fire threat is quite suitable for the residents during an evacuation. The time to evacuate residents is known as RSET. The most crucial feature of the residents' security is the possibility of having enough time to evacuate the area if a fire breaks out. The ASET indicates when conditions are no longer tenable. The fire effect's tenability limit, as established in the acceptance criteria, is the point at which the ASET is decided. RSET is calculated by analyzing how long it took for the passengers to reach safety after the fire. As a result, the evaluation of the admission criterion is ultimately based on how securely occupants may flee a fire hazard's presence.

In a study by Frantzich [19] two approaches assessed fire risk for building occupants. Standard Quantitative Risk Assessment (QRA) and Extended QRA treat variable uncertainty differently, with the latter explicitly addressing it. To grasp uncertainty, sensitivity analysis was done alongside standard QRA. Both methods calculated societal risk for a hospital ward, using Monte Carlo simulations. These methodologies helped identify cost-effective design alternatives for risk mitigation. Risk measures included individual and societal risks, primarily illustrated by average societal risk. The study aimed to evaluate patient risk in a hospital ward, with extended QRA offering a more reliable risk measure due to its explicit handling of uncertainties.

The evaluation of fire risks is of utmost importance to guarantee the safety of engineering and fire science systems. The Fire Risk Assessment Method for Engineering (FRAME) employs a pre-established index system to evaluate the hazard of building fires, which results in a more convincing approach compared to other methods as it avoids the subjective influence of false positives. Guo [20] investigated the advantages of FRAME and its calculation methodologies by analyzing a commercial building located in Shijiazhuang, China. Based on the method, stronger fire protection measures were recommended to enhance the safety of the building. The FRAME approach is used to assess fire risk but has flaws, including outdated data and irrational factors. More

innovation and research are needed to improve it.

Leiras et al. [21] propose an enhanced fire safety standard that aims to eliminate fire-causing conditions and reduce the impact of fires on people and infrastructure. They suggest a comprehensive fire risk assessment method that examines critical elements' potential failures to enhance building fire safety. This method addresses issues with existing risk analysis techniques and employs a redundant process to reduce uncertainty. It assesses fire risk by considering probability, severity, exposure, and compares expected performance to actual results, calculating fire spread and evacuation possibilities. A structural fire safety evaluation methodology, incorporating risk factors and human exposure, is developed using Priority Analysis of Safety Markers (PAI) to minimize uncertainties. This approach offers dynamic and reliable fire risk analysis for comprehensive management.

Fire codes and regulations, like IFC, NFPA, NBC, and GRIHA, are vital for fire safety across sectors. Further research is needed to improve these standards. This includes assessing how well current codes prevent fires and minimize damage, adapting to new technology, and addressing emerging fire safety challenges. Such research will strengthen fire prevention and protection measures. Fire safety regulations have evolved from prescriptive to performance-based methods. This shift is driven by limitations in assessing complex designs and high compliance costs. Performance-based approaches prioritize objectives over specific solutions, offering flexibility and cost-effectiveness. Modeling and simulation, such as ASET and RSET models, are vital for assessing performance-based rules, predicting behavior during fires, and ensuring safe evacuations. These measures prioritize resident safety in fire situations.

Fire risk assessment methods are crucial for building safety but have limitations due to various scenarios and subjectivity. Researchers explore quantitative approaches like standard and extended QRA to handle uncertainties. FRAME reduces subjectivity and suggests safety improvements, while a new technique targets critical element failures to enhance fire safety.

2.2 Fire Resistant Building Material

Fire-resistant building materials are designed to resist combustion, slow down the spread of flames, and provide a higher level of protection against fires. These materials are crucial

for enhancing the safety of structures and reducing the risk of fire-related damage. Characterizing and establishing the fire performance of innovative building materials under various fire design scenarios is crucial. Modern prescriptive-based techniques sometimes overlook new materials' fire design challenges, such as concrete spalling and the rapidly degrading strength of Fiber Reinforced Polymer (FRP) composites. To guarantee the excellent fire performance of novel building materials, before using them in buildings, how they act in a fire scenario should be studied.

There are few studies on how hazardous and combustible a material can be; whereas the majority of the emphasis of available studies is on describing how new materials lose strength. High toxicity can make it riskier for people to survive, yet high combustibility can exacerbate flames by accelerating their spread and growth. To make educated judgments about the usage of novel materials in structures, three fire safety factors—toxicity, strength degradation, and combustibility—should all be studied in detail [10]. Some research regarding fire-resistant building materials is as follows:

Wang and Wang [22] conducted a thorough study on fireproofing materials for steel structures. Their research aimed to evaluate the effectiveness of various coatings and insulating materials in protecting steel structures during fires. They explained their experimental methods, presented test results (temperature profiles, structural integrity, and protection duration), and analyzed different materials. This study has practical implications for architects, engineers, and building safety standards, aiding in the selection of fireproofing materials for safer steel-framed buildings.

In an investigation done by Nodehi [23] on the behavior of non-structural and structural glass at high temperatures, focusing on their potential as structural elements and fire resistance. The research employed a Displacement Analyser (DIANA) finite element model to simulate glass tests conducted by Empa researchers in Switzerland. The model revealed that heat-specific properties significantly influenced glass temperature. Experiments conducted at Efectis Netherlands examined the fire behavior of annealed, fully tempered, and heat-toughened glass under various conditions. The results highlighted the vulnerability of annealed glass to thermal breakage due to temperature fluctuations, emphasizing the importance of careful joint design when using glass as a fire-resistant structural component in conjunction with steel at high temperatures.

Aldefae et al. [24] studied the fire resistance of common construction materials to assess their performance in fire conditions, enhancing building safety. They tested how cubic concrete specimens and clay bricks reacted to a 600°C temperature to understand their behavior during fires. Numerous concrete specimens at 7 and 28 days and bricks from various locations were extensively tested. The research examined how high-temperature exposure affected their compressive strength and the impact on clay bricks in terms of efflorescence and water absorption. It was found that both clay bricks and concrete lost strength when exposed to higher temperatures. At high temperature brick's efflorescence increased, while water absorption decreased.

In the study done by Zhu [25] to develop innovative fire-resistant coating materials, namely High-performance cement mortar (HPCM), Geo-polymer mortar (GPM), and Magnesium phosphate cement mortar (MPCM), and assess their feasibility for structural fire protection. These materials were formulated as mortars and evaluated for workability, early-age strength, and setting time. HPCM exhibited the highest compressive strength, while all three materials demonstrated good slip resistance, cohesiveness, and adhesiveness as coatings. They also acted as heat insulation to delay heat transfer into protected structures. However, HPCM lost its insulation properties above 650°C, while GPM remained effective up to 950°C, and MPCM maintained integrity even at higher temperatures. MPCM showed the best overall fire resistance.

Findik [26] stressed the importance of selecting fire-resistant construction materials like steel and concrete to enhance building safety. Materials like expanded aggregate and mineral fiber are used to insulate against high temperatures. Global construction codes include fire resistance standards for various building parts, with some countries mandating sprinklers and other safety measures. Ensuring building safety requires thoughtful consideration of structural systems in new or renovated constructions.

Zhou et al. [27] investigated the fire resistance of concrete beams incorporating iron tailings sand. The aim was to evaluate the performance of these concrete beams under high-temperature conditions. Through a series of experiments, the researchers assess parameters like structural integrity, load-bearing capacity, and thermal conductivity. The findings reveal valuable insights into the suitability and effectiveness of using iron tailings sand in concrete production for applications where fire resistance is a critical factor. This

research contributes to a broader understanding of sustainable materials in construction and their performance under extreme conditions.

Fire-resistant materials are vital for safeguarding structures, mitigating flame spread, and minimizing damage. Evaluating their performance in diverse fire scenarios, considering factors like toxicity, strength, and combustibility, is crucial. Recent studies have assessed fireproofing coatings and insulating materials for steel structures, benefiting architects and engineers. Another study compared fire resistance in common construction materials, aiding material selection for safety. Innovative coatings like HPCM, GPM, and MPCM were developed and evaluated, with MPCM exhibiting superior fire resistance. Further research will focus on refining mix designs, surface performance, and cost-effectiveness analysis.

2.3 Enhancement in Fire Resistance of Concrete in Buildings Exposed to Fire

Enhancing fire resistance in concrete for buildings exposed to fire is crucial for safety and property protection. Approaches like adding fire-resistant additives, using coatings, and advanced structural design ensure concrete can withstand high temperatures, preventing spalling and maintaining structural integrity. These measures buy valuable time for evacuation and firefighting, contributing to safer, more resilient structures in an urbanized world with persistent fire risks.

The study by Mathews et al. [28] examined how protective coatings affect the fire resistance and load capacity of Self-Compacting Concrete (SCC) in short columns. SCC incorporates eco-friendly materials like Fly Ash and Ground Granulated Blast Furnace Slag (GGBFS), and replaces fine aggregate with Expanded Perlite Aggregate (EPA). A Cement Perlite Plaster (CPP) using Ordinary Portland Cement and EPA was developed for thermal protection. Testing was done under ISO 834 fire standards, with GGBFS-based SCC outperforming other variants. CPP-coated SCC displayed the highest residual strength, surpassing gypsum plaster, basalt wrapping and carbon wrapping - protected SCC under load.

Abdulrahman and Kadir [29] observed high-strength reinforced concrete beams in fire and tested the effectiveness of reinforcing them with CFRP laminates. Ten beams were examined under varying fire durations and grouped accordingly. Results indicate all beams failed due to flexural stress, with minor spalling. The beam exposed to two hours of fire

lost 12% strength but had similar deflection at failure as the control beam. CFRP reinforcement significantly reduced fire damage, restoring stiffness. Beams with compression faces exposed to fire had a greater strength reduction compared to those with tensile faces exposed. Ductility decreased by about half for beams exposed to fire for 90 and 120 minutes.

Nine concrete slabs in three groups: S0 (control), S45 (45 mins fire exposure), and S75 (75 mins fire exposure) were tested by Van Cao et al. [30]. After fire exposure, two slabs from each group were reinforced with FRP. Fire slightly reduced ductility but still exceeded 4, indicating high ductility. It marginally decreased yield and ultimate strengths but significantly reduced stiffness by about 30%. Adding 1/2 and 1 layer of FRP increased yield strength by 30% and 45%, and ultimate strength by 46% and 65%, respectively. Cyclic loading had a minor impact on strength but reduced stiffness by 20% (1/2 FRP) and 35% (1 FRP). A theoretical model was created to estimate FRP retrofitted fire-exposed slab capacity for practical engineering use.

In a real-world scenario with a 12-story reinforce concrete structure exposed to fire, maintaining stability is crucial. High fire temperatures lead to reduced stiffness and load-bearing capacity of concrete and steel reinforcement due to physio-chemical changes. In their study, Guruprasad and Yashwanth [31] examined two compartments exposed to high temperatures (300°C, 500°C, and 700°C), finding that the interplay of temperature and gravity stresses worsens structural damage, causing nonlinear deformations like column buckling and beam bending. Retrofitting damaged parts with RC jacketing improves overall stiffness and stability, enabling elements to withstand external stresses more effectively.

Kim et al. [32] studied the interaction diagrams of fire-exposed Concrete-Filled Steel Tube (CFST) columns, focusing on the slenderness effect. They found that slenderness ratio greatly influences CFST column's fire resistance, urging careful design consideration. Steel and concrete material properties played a crucial role, leading to practical design suggestions for better fire performance. This research provides key insights for structural engineering, stressing slenderness in evaluating CFST column behavior during fire, with implications for safer designs in fire-prone areas.

The research emphasizes the importance of considering slenderness ratios in designing CFST columns for fire resistance. It also highlights the significant impact of high-

temperature fire exposure on reinforced concrete (RC) structures, particularly in terms of column and beam stability. The study explores protective coatings for SCC columns and their fire resistance. Additionally, it demonstrates the effectiveness of CFRP laminates in preserving high-strength reinforced concrete beams under fire conditions and proposes retrofitting solutions for fire-exposed reinforced concrete slabs using FRP. These findings have practical implications for safer and more resilient construction practices in fire-prone environments.

2.4 Structural Adequacy Analysis of building Exposed to Fire

Structural adequacy analysis of buildings exposed to fire is a critical aspect of ensuring the safety and resilience of our built environment. When a fire breaks out in a building, it subjects the structural elements to extreme temperatures, which can weaken and compromise their integrity. Engineers and fire safety experts conduct rigorous assessments to determine if a structure can withstand these thermal stresses and maintain its load-bearing capacity during a fire event. This analysis involves evaluating various factors, including the materials used, the design of the building, the fire resistance of structural components, and the duration and intensity of the fire. By conducting such assessments, we can develop fire-resistant building designs using contemporary software and select appropriate materials. Also, implement fire protection measures to enhance the structural resilience of buildings, ultimately safeguarding lives and property in the event of a fire emergency.

Huang and Tan [33] studied how steel columns behave when exposed to external moments and heating systems. They used Finite Element Method Fatigue (FEMFAT) software to analyze uniform cross-sectional members. The pin-roller columns' critical temperature can be lowered by external moments. But not rotationally restricted steel columns. Quick and slow heating strategies were also examined, with creep being observed at slower rates and at 450°C.

In their research, Li and Purkiss [34] provided a crucial assessment of models for concrete’s mechanical behavior at extreme temperatures. A stress–strain–temperature model was generated using the same models and their experimental results, which implicitly integrate the influence of transient strain. This concept was simple to implement into the finite element analysis tools available commercially. A mathematical illustration using a wall element heated on two opposing faces demonstrates that transient strain does

not play a significant role in the early stages of heating; nonetheless, when exposure duration gets longer, the impact of disregarding brief tension gradually gets stronger, resulting in retrogressive load carrying capacity forecasts.

Huang [35] used a Three Dimensional (3D) finite-element method to analyze fire's impact on reinforced concrete structures. His approach includes material and geometric non-linearity, addressing concrete spalling within slabs, beams, and columns. The modeling data highlights the importance of gravity columns for structural stability during fires. Keeping all components same of fire resistance rating, gravity columns are the first to fail. Better connections can prevent this failure and improve ductility during cooling.

Sun et al. [36] developed a novel technique that integrates static and dynamic simulations to enhance the Vulcan software's efficiency in simulating steel structures subjected to fire scenarios. This innovative software automatically switches between static and dynamic analysis and has undergone rigorous testing using real-world scenarios to evaluate the gradual structural collapse of these structures. The results of these tests demonstrated the effectiveness of this technique.

An open-source finite element software called OpenSees, used for modeling high-rise structures in fire scenarios. It was developed by Kotsovinos [37] at the University of Edinburgh and adheres to the object-oriented paradigm. The program underwent investigation, verification, and validation, including a dynamic study of the structure under fire for collapse evaluation. With its structural fire capabilities, engineers can now collaborate globally using a community platform to effectively analyze and evaluate structural designs.

Jiang et al. [38] used OpenSees software to study how travelling flames affect a large building's fire response. The "equal area" method doesn't work well for assessing fire resistance. Small flames create high temperatures in concrete, while large ones cause steel beams to fail faster. Concrete slabs create thermal gradients in beam sections, with larger flames producing higher gradients. Flame size doesn't affect maximum temperature gradients on concrete sections.

Agarwal et al. [39] observed the collapse resistance and fire behavior of middle-height steel structures with floors having composite floors. They constructed 2 steel structures, having 10 floors each, one with a perimeter lateral load system and the other

with an interior system, compliant with American design standards. The buildings were simulated under fire conditions using Finite Element numerical methods with explicit dynamic analysis.

Gravity columns are essential for a building's fire resilience. Proper shielding maintains their strength, but stronger connections are needed to avoid failure during heating and cooling. Steel columns were studied by Agarwal et al. [40] using numerical and experimental methods to validate the finite element method. Insights from these experiments can enhance building design. Factors like slenderness, axial stress, and heating arrangement affect column strength and failure, including buckling along strong and weak axes. Uniform heating leads to higher failure temperatures, except for thin columns under heavy loads. Design equations were created for columns with broad flanges and thermal gradients.

The codes of practice for designing structures for the event of a fire were frequently ignored. The collapse of the World Trade Center, Windsor Tower, and Delft building had prompted concerns about the structure's stability in the case of a fire. The worldwide collapse of the building as a result of multi-floor fires has been demonstrated in several events. Vismitha et al. [41] used ETABS to investigate the reaction of a building at various temperatures, culminating in its collapse at a specific temperature. The seismic analysis was also performed on the same structure using SAP2000's static pushover analysis.

The behavior of steel and concrete elements in fires scenarios using finite element analysis and experiments are discussed. It emphasizes the significance of gravity columns and stronger connections for structural stability in fires. Innovative simulation techniques show promise for advancing structural engineering. Also, multiple methods are tested and evaluated to identify the most effective approach based on key criteria. These findings provide valuable insights for designing safer and more resilient structures.

2.5 Retrofitting of building exposed to Fire

Retrofitting is the process of improving existing building structures and making them more usable. Numerous existing structures all throughout the world require urgent retrofitting and rehabilitation due to a variety of causes, including inadequate detailing, environmental impacts, and poor maintenance and fire occurrences.

Mukhopadhyay et al. [42] introduced condition monitoring and structural retrofitting for

historic buildings, including a case study. The goal was to assess old building conditions for safety, considering factors like earthquakes and deterioration. This research suggested reinforcing methods (fiber-reinforced polymer and concrete jacketing) and evaluated their pros and cons from an engineering perspective. The aim was to demonstrate expertise in building assessment and reinforcement, not to introduce new assessment methods.

Vasudeva and Kaur [43] investigated two sets of beams with differing strength issues in the same concrete grade. They retrofitted some beams with Glass Fiber Reinforced Polymer (GFRP) sheets. In one set, reinforced beams with flexural problems at different points using GFRP sheets, while in the other set with shear issues, they applied U-jacking and GFRP sheet reinforcement at the edges of some beams. The study assessed the failure of these modified reinforced concrete beams using an asymmetric two-point loading method. Each GFRP orientation recorded failure mechanisms. Retrofitted beams showed increased load at first fracture and final collapse compared to control beams, mainly failing in flexural shear. Simultaneous flexural and shear retrofitting was recommended. Set B beams shifted from shear to flexural failure, demonstrating shear zone retrofitting's efficiency for both shear and flexural failure.

During the research, Bhattacharyya et al. [44] observed building/structure fires in the past have increased structural system's vulnerability to such occurrences, necessitating post-fire retrofitting efforts if the structures do not collapse. It was critical to have prior knowledge about structural member residual strength in order to do effective retrofitting. However, determining the residual strength was challenging due to a lack of knowledge about the exposure temperature of the structural parts. Although concrete has considerable fire resistance due to its low heat conductivity, prolonged exposure to high temperatures damages its technical qualities and diminishes its overall structural capacity.

In a study by Thomas and Hameed [45] the impact of temperature changes on concrete, both at macro and micro levels, focusing on factors like fractures, thermal expansion, and mix ratios were observed. Microscopic analysis delved into porosity and chemical effects on concrete's fire resistance. The goal was to predict heat exposure in fires by connecting high-temperature micro-structural changes to strength. The study experimented with retrofitted reinforced concrete beams using cost-effective ferrocement, finding that unwrapped welded mesh performed best in terms of crack patterns, load-deflection, torque-twist response, and load-strain characteristics.

An experimental investigation by Durgadevi et al. [46] entails enclosing M30 reinforced concrete beams using basalt fiber reinforced polymer (BFRP), glass fiber reinforced polymer (GFRP), and carbon fiber reinforced polymer (CFRP) to determine their load-bearing capability and deflection under service load. Bi-directional fiber layers were used to wrap the double and four layers. Four layers of wrapping on an externally bonded FRP made it more resilient to force from the outside and reduced deflection compared to other FRPs.

The critical practice of retrofitting existing building structures to enhance their usability and safety. It emphasizes the urgent need for retrofitting due to various factors like inadequate design, environmental impacts, maintenance issues, and the risk of fire incidents. Several research studies are mentioned, covering topics ranging from condition monitoring and retrofitting methods to the mechanical behavior of materials under extreme temperatures. The experiments with different retrofitting materials like BFRP, GFRP, CFRP provide insights into improving load-bearing capacity and reducing deflection in retrofitted structures. Overall, the importance of retrofitting in guaranteeing the security and toughness of old structures in a world that is changing quickly.

2.6 Findings from Literature Review

The findings from an extensive literature review on building safety in the context of fire cover a range of critical aspects. This thorough examination delved into rating systems, standards, materials resistant to fire, approaches to improve the fire resistance of concrete buildings, analysis of structural adequacy, and the retrofitting of buildings after exposure to fire. One notable revelation is the inadequacy of existing codes and standards to accurately represent real-world building fire scenarios. This shortfall raises concerns about the reliability of current regulatory frameworks in ensuring optimal safety measures. Furthermore, the criteria and credits outlined in prevailing building codes were found to be insufficient in addressing the nuanced aftereffects of fire on building components, highlighting a need for more comprehensive considerations in future standards.

In addition to the limitations in existing codes, the study identified that traditional approaches to evaluating fire resistance tend to be overly conservative. This could result in an overestimation of safety measures or unnecessary costs. Notably, in the specific context of the Indian built environment, the research highlighted a significant gap—limited studies have been conducted on the impact of traveling fires within buildings. This gap

underscores the necessity for context-specific research to inform more tailored safety guidelines and regulations.

Another finding emphasizes the complexity involved in retrofitting and reusing buildings following exposure to fire. This process requires not only structural analysis but also a nuanced appraisal of structural adequacy to ensure that repurposed structures maintain a high level of safety. Such considerations are particularly crucial when dealing with situations where only a small portion of a building has been exposed to fire. In conclusion, these findings collectively underscore the imperative for a more nuanced, context-specific, and comprehensive approach to building fire safety, addressing both pre-fire prevention and post-fire structural considerations. This holistic perspective is essential for enhancing the resilience and safety of buildings in the face of fire-related challenges.

3. RESEARCH GAPS

The following research gaps have been drawn after a thorough literature review of rating systems and norms, fire-resistant building materials, concrete building fire resistance enhancements, structural adequacy analysis and retrofitting of building exposed to fire.

1. Existing codes & standards do not depict an accurate building fire situation.
2. Criteria & credits in current building codes and standards do not cover the aftereffects of fire on building components adequately.
3. Current fire protection measures have an un-quantified level of fire safety in buildings.
4. Traditional approaches to evaluating fire resistance are over-conservative.
5. Current measures are not cost-effective.
6. Not many studies have been done on travelling fires in buildings in an Indian context.
7. Retrofitting and reusing buildings when a small portion is exposed to fire requires structural analysis and an appraisal of structural adequacy.

4. DESCRIPTION OF BROAD AREA

Rapid urbanization in India is leading to a scarcity of land in metropolitan areas. This has made constructing high-rise buildings the primary option for accommodating the growing population. While high-rises offer advantages like better views, reduced noise, and lower construction costs compared to lower buildings, they also face a significant fire risk. Urban areas with dense populations are particularly susceptible to fire incidents, which are on the rise with urbanization. Xin and Huang [47] explained that high-rise buildings pose unique challenges in firefighting due to increased wind speeds at higher altitudes and the stack effect. Evacuation and firefighting become more difficult in densely packed structures. Additionally, winds facilitate the spread of fire between different levels. In India, extinguishing fires externally is complicated by the prevalence of multipurpose and small buildings. Insufficient fire prevention measures, challenging firefighting efforts, and ineffective escape plans contribute to increased fire losses.

More than 39.2% of the buildings in Mumbai, one of India's largest metropolises, that had fires between 2020 & 2021 lacked functional firefighting & rescue systems [48]. Therefore, to guarantee that fires are prevented and treated as efficiently as possible. A thorough risk assessment of every high-rise structure is required. This research’s primary objective is to offer a complete approach to evaluating the fire risk in tall building structures housing people in India.

A fire-damaged concrete structure can be demolished, rehabilitated or retrofitted using certain measures. Rehabilitating the structure may be, in most situations, economically efficient, depending on the damage to the structure. Assessing the structure is essential in order to formulate a well-organized solution for the issues at hand. One of the main objectives is to go forward with the restoration of the fire-damaged structures by conducting a thorough visual inspection and studying the structural material properties at the exposed temperature via various tests.

It is not simple to construct attractive structures that are strong enough to resist any adverse situation like an earthquake or fire. The technology has made significant strides in practically every industry today, which is precisely why engineering has to keep up with the profession's rapid technological advancement. As a result, the way engineers perform and operate has changed in numerous ways. Technology has not only made life simpler,

but it has also inspired engineers to produce more as a result of the creation of some fascinating applications.

Multi-story building analysis and design are done using contemporary software. The distinctive grid-like shape of this type of building is considered using modeling tools & templates, code-based load guidelines, analytical methodology, and solution approaches. It is possible to analyze statically and dynamically both basic and complex systems with software. The structural analysis software is essential for doing the fire calculations for the facilities. Traditional approaches are no longer sufficient for analytical work in this modern-era world. The use of new technology is essential because architecture and design have evolved so competitively over the years.

ETABS (Extended 3D Analysis of Building Systems) is powerful structural engineering software known for its advantages. It offers built-in drawing utilities that simplify modeling and deliver high-quality results. ETABS also stands out for its comprehensive reporting capabilities, covering stress calculations, deformation analysis, and design summaries.

The software accommodates Large-Displacement & P-Delta effects for assessing fire-related building performance through modal and direct-integration time-history analysis. Its integrated features support the creation of complex applications, from basic 2 Dimensional frames to contemporary high-rises. It includes specialized modules for concrete and steel frames, addressing common building materials and streamlining calculations and capacity assessments. These qualities make ETABS a preferred choice for structural engineers in their analysis and design work.

5. RESEARCH OBJECTIVES

Based on the theoretical framework for the investigation and literature review in the area of building site safety and fire risk assessment, the following study assessments were developed as the objectives of the research:

1. To analyze the quotient of fire safety norms in Existing Buildings Standards.

2. To develop a criteria framework for Fire Safety Ratings of Existing Buildings using Rapid Visual Screening.

3. To simulate how high-rise structures respond to individual and combined cases of vertically & horizontally travelling fire.

4. To perform parametric evaluation studies to examine the processes that causes the generic high-rise to collapses in the event of a fire.

5. To recommend criteria & credits related to fire exposure to be included in building codes & standards.

6. RESEARCH METHODOLOGY

The research is a targeted investigation of certain activities for the benefit of the organization and society. Issue identification, study design, data gathering, data analysis, and result interpretation are the five steps of the research process. After a rigorous study, it was decided to do research in the field of existing buildings exposed to fire. To start with, an extensive literature review was done to get to the root of the problem faced if a fire incident occurs in an existing building. During the review, different standards & norms were studied to analyze different types of conditions that are available on National & International levels. NBC 2016 is the renowned code that is used in India.

Accordingly, a criteria framework will be developed for Fire Safety Ratings of Existing Buildings using Rapid Visual Screening. Further, to understand the behavior of the building exposed to fire, different models will be generated & analyzed using appropriate software. A high-rise building will be generated and different permutations & combinations of fire cases will be applied to the building models. The behavior of high-rise buildings under horizontally and vertically travelling fires, separately and in combined scenarios will be analyzed.

During the analysis of the models, a detailed study will be done to observe the collapse mechanisms of the high-rise buildings in the foreground. Also, these mechanisms of occurrence will be observed by conducting a series of parametric studies.

After analyzing all the data, a conclusion will be made, and from these conclusions, new recommended criteria & credits will be proposed in building codes & standards. Recommendations for criteria & credits will help in the future to build better and safer high-rise buildings.

Also, appropriate retrofitting techniques & measures would be suggested based on the analysis and re-design.

Various steps of this research work are shown in Fig. 1.

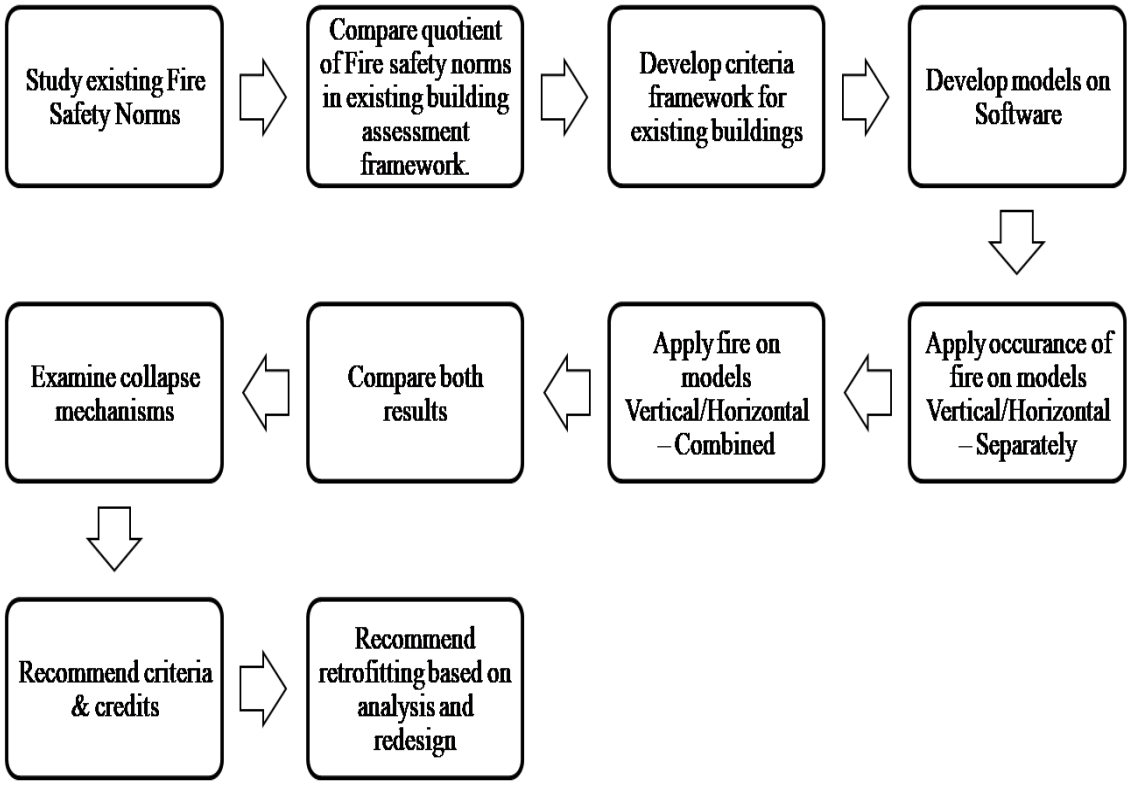
Study existing Fire Safety Norms
Compare quotient of Fire safety norms in existing building assessment framework.
Develop criteria framework for existing buildings
Develop models on Software
Apply occurance of fire on models Vertical/Horizontal – Separately
Apply fire on models Vertical/Horizontal – Combined
Compare both results
Examine collapse mechanisms
Recommend criteria & credits
Recommend retrofitting based on analysis and redesign

Fig. 1: Methodology

7. EXPECTED OUTCOME OF THE RESEARCH

This research focuses on the identification of the criteria for retrofitting fire-experienced buildings. The research will help in providing a better quotient of Fire safety in International/National building performance rating systems. Also, a literature review was conducted to observe the research gap in the field of fire-experienced buildings.

The following are the expected outcomes from this research work:

1. A better quotient of Fire safety norms for the existing building assessment framework.
2. Fire protection measures at a quantified level of fire safety in buildings.
3. Criteria & credits recommendations to be included in existing building standards.
4. Collapse mechanisms after parametric studies of building structural analysis.
5. Recommend levels of retrofitting measures & techniques for buildings exposed to fire events.

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